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Understanding systemic analysis in the governance of sustainability transition in renewable energies: The case of fuel cell technology in Iran

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ABSTRACT

Considering the complex and evolutionary process of renewable energy development, it is imperative to have a framework for its governance. The governance of transition toward renewable energies can be divided conceptually into two phases, namely systemic analysis and policy making. This paper focuses on identifying different methodological steps in the systemic analysis phase. These steps provide requisite inputs for the second phase, policy making, by attaining a concrete understanding of the current status. In the first step, the boundaries of the transition process are defined by specifying the unit of analysis and identifying the system's components and relations. In the second step, and in order to have a big picture of the system's transformation, the dynamism of technological development is mapped through time. In the third step, an approach for analyzing and policy making of sustainability transition is chosen by comparing various approaches and selecting the most fitted one. All of these methodological steps are finally applied in the case of the Iran fuel cell technology development program to show the practicality of the proposed conceptual framework in a real case problem and to provide some insights for practitioners.

Contents

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1. Introduction

Although the most important source of energy in the world will be fossil fuels up to 2030, numerous countries strongly prefer to move toward a new source of energy named renewable energies (REs) [1]. In the same manner, Iran has also focused on developing different renewable energies from 20 years ago. Obtaining 44 and 54 percent of its energy from oil and gas, Iran is one of the biggest suppliers of fossil fuels in the world [2]. Nevertheless, forecasting the great demand for energy in the future as a developing country on one hand, and stressing the vitality of sustainable development on the other, motivates Iranian policy makers to attend to REs' development as a future source of energy. In this respect, fuel cell (FC) technology has been one of the selected options for electricity generation by Iran's government and energy sector in the past fifteen years. Iran has given priority to the fuel cell technology development because of the 9 to 10 percent annual growth in electricity demand up to 2025,[1] the ability of producing energy twice more efficiently than existing fossil plants, the emphasis of the government on distributed electricity generation due to inefficient transferring lines, and finally, the emergence of fuel cell motor engines [3].

Contrary to the countries' interest in developing REs, it is not easily achievable. The current system of energy has been evolved into a complex and inter-correlated set of actors, technologies, and institutions, which Unruh [4] "named carbon lock-in". In such conditions, the development of renewable energies needs a continuous stimulation to break the system's structural inertia and to build a new order. This process is referred to as "Transition" in the literature [5]. Transition is a process in which the social system is changed, existing structures are broken down, technological, political, and economical innovation occurs, and necessary driving forces are provided for change [6,7]. Researchers have also considered the subject of sustainability and presented the concept of "Sustainability transitions". According to their definition, sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes that shift current socio-technical systems to more sustainable forms of production [8]. The gradual development process of REs technologies such as fuel cells can be considered a sustainability transition by this proposed definition.

Being a relatively long-term process, the sustainability transition toward REs should be considered as a complex-evolutionary system [9]. Some features including the existence of nonlinear relations, feedback loops, instability, varying boundaries, and numerous subsystems prove the complexity of such systems [10]. Besides, the other features including the dominance of dynamism, focus on innovation, system heterogeneity, actors' bounded rationality, and finally path dependency indicate the evolutionary aspect of this system [11]. Such systems are not developed spontaneously. They need a guiding power to show the right path of development. Hence, guidance and governance play significant roles in sustainability transition. A conceptual framework that is able to manage complex-evolutionary systems coherently can play this role [12].

The literature on sustainability transition and conceptual frameworks for its governance is highly broad. Recently, a paper has been published by Markard et al. [8] that investigates sustainability transition studies and classifies them into four core research streams comprising technological innovation systems (TIS), multi-level perspective (MLP), strategic niche management (SNM), and transition management (TM). Various researches have been carried out on the governance of renewable energy development from these points of view. They are classified into two major groups according to their overall goal: reviewing the theoretical concepts of sustainability transition and establishing methodological frameworks for analyzing the current status or policy making of real cases. In the first group, Coenen and Díaz López [13], by comparing existing approaches in innovation systems from different aspects including system boundary, actors and networks, institutions, knowledge, dynamism, and policy approach, have provided a clear picture of innovation policy models. Chang and Chen [14] have also explored the innovation systems literature, compared them from three perspectives including knowledge links, knowledge transfers, and system's boundary, and finally discussed some methodological challenges in that area. Furthermore, Markard and Truffer [15] have clarified commonalities, differences, strengths and weaknesses in two approaches, technological innovation systems and multi-level perspectives, by introducing basic concepts and system boundaries in each model. In addition to the first group, the other research group intends to develop a methodological or operational framework for guiding REs' development. In this group, Carlsson et al. [16] have applied a systemic approach in the area of innovation systems and stressed the necessary methodological aspects of the technological innovation system (system boundary, level of analysis, and performance). Based on the theoretical and empirical literature, Soltani and Kiamehr [17] have proposed a conceptual framework for formulating national science, technology, and innovation strategies using an interdisciplinary research method. Musiolik and Markard [18], Markard and Truffer [19], and Truffer et al. [20] have assessed technological innovation systems from three perspectives of networks, actors, and institutions, respectively. These three papers develop operational frameworks for analyzing the structure of innovation systems.

In the research that was just reviewed, different useful comparisons, methods, and models have been presented. They are fairly deep studies covering all facets of RE development. However, in order to successfully direct the sustainability transition in REs, a coherent and holistic framework is needed that encompasses all aspects of sustainability transition, from the analysis of the current status (as is) to policy making of the development process (to be). With respect to the mentioned framework, it is believed that it should consist of two major phases: systemic analysis and policy making. In the systemic analysis phase, the understanding of components, relations, dynamisms, and inducing and blocking mechanisms, which affect RE development, is provided. In the policy making phase, targeted measures are formulated for facilitating the transition process to RE based on the obtained knowledge of the first phase. The questions that will arise are what are necessary methodological steps in performing each aforementioned phase? This constitutes the main research question of our study.

For the beginning, the main idea of the study is concentrated on an explanation of the systemic analysis phase, and digging into

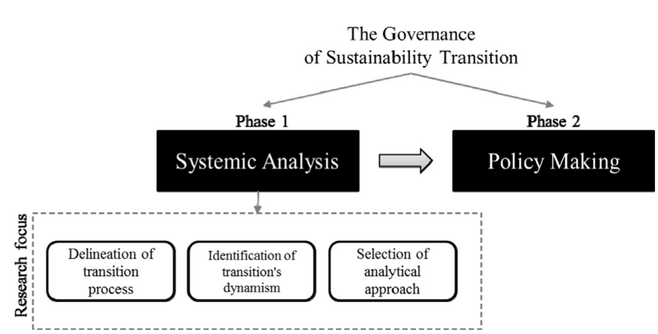

Fig. 1. The research focus of the paper in governance of sustainability transition.

[1] Iran 2025 Vision (www.IREC.ir).

the policy making phase is set aside for future research. In this paper, three methodological steps are proposed to investigate the systemic analysis phase in sustainability transition: delineation of the transition process, identification of the transition's dynamism and evolution, and selection of an approach for analyzing RE transition (Fig. 1). These steps provide a big picture from the current status that is a required input for prosperous policy making in the second phase. Although this paper is explorative-conceptual in nature, it also presents some empirical results from the case of fuel cell technology in Iran.

The paper is organized as follows. After the introduction in Section 1, three consecutive methodological steps are proposed in Section 2. Next in Section 3, the developed steps are applied in a real case, Iran fuel cell technology development. Finally, Sections 4 and 5 elaborate and summarize the main characteristics and contributions of the study and discuss future opportunities for research in this field.

2. Methodological steps

This section aims at listing the steps required for the systemic analysis of the current status in sustainability transition. The principal contribution of this section is to propose a clarified and unified picture of components in each step and to provide the required input for future political decisions.

2.1. Delineation of transition process

At the beginning of the systemic analysis phase, the boundary of the transition process should be specified. Delineation helps policy makers to distinguish internal factors affecting the development process from external ones. It also increases the ability of policy makers to design more pertinent transition policies [21]. One viable way for defining the boundary of subjects is to use the System Theory [22]. A system is a theoretical concept, which can be applied in a diverse range of applications. According to Markard and Truffer [15], the transition process is delineated from two perspectives: descriptive delineation and conceptual delineation. On the one hand, descriptive delineation determines the breadth and depth of the subject which policy makers should consider, and on the other hand, conceptual delineation identifies internal components and relations engaged in transition. Taking both perspectives into consideration clarifies further steps in the governance of the transition process. Here, a detailed description of each branch of delineation is proposed.

2.1.1. Descriptive delineation

A system in the transition can be analyzed at three different levels or units: technology as a knowledge field, product, and competence bloc (Table 1). The chosen unit will influence the breadth and depth of factors policy makers should consider in their analysis. In other words, it helps them know the level of the transition process which their policy measures should concentrate on.

Table 1
Units of analysis in technological innovation systems (modified from [16]).

Unit of analysis	Purpose
Technology (knowledge field)	Analysis of technology and its sub technologies, considering their usability in various applications and products
Product	Focus on a product and its related technologies and applications
Competence bloc	Analysis of a specific market and a set of incorporated products required for a sector

Selecting technology as the unit of analysis converges all attempts for research and creation of knowledge as the basis of technology growth. Consequently, the main part of policy measures will be related to facilitation of the transition process in research institutes, universities, and other knowledge oriented components of the society. If a product is selected as the unit of analysis, the policy initiatives would mainly be connected to the transformation of knowledge to practical products. In this situation, major attention is devoted to capability building and development of domestic products in the industry. Finally, choosing a competence bloc points towards the handling of a group of interrelated technologies and products used in a focal market. Policy interventions in this case will be related mainly to stimulating a sector's growth.

2.1.2. Conceptual delineation

Conceptual delineation separates a system in transition from its environment by assuming that the relations among a system's components are significantly stronger than the relations between the system and its environment. The principal aim of conceptual delineation is to discriminate between internal and external factors that influence the development of REs [23]. Based on the selected unit of analysis in descriptive delineation, conceptual delineation tries to understand the system's structure in four categories: actors, institutions, networks, and technologies [15].

Actors are part of the system's structure that perform activities to contribute to the innovation in the transition process. They may be involved in the creation of knowledge (such as universities and research institutes), development of technologies and products (such as entrepreneurs and production companies), and guidance and governance of a development process (such as governmental agencies and ministries). Each actor carries out activities by using resources, based on their strategy and in the institutional frameworks set in the environment [24]. The activities are performed in some functional areas that are needed for RE development. The level that these functional areas are fulfilled determines the performance of sustainability transition. With respect to the mentioned role of actors in system performance, their identification assists policy makers in acquiring two points: first, they can determine the actual and potential role of actors in the fulfillment of systems' functions and performance; second, they can find structural alternatives which may elevate the systems' performance in the policy making phase [19].

The second component is institution. Institutions are defined as rules of the game [25]. In our case, institutions are terms and conditions, laws, norms, rules, habits, and standards which stimulate or discourage socio-economic behaviors [26]. They decrease the uncertainty of systems and provide stability in technological growth by defining a concrete framework for doing activities. They are classified under various dimensions [13,20,27,28]. Among these are four dimensions that are presented in Table 2. In this table, type states the quality of enforcement mechanisms, sector defines the applicable range of institutions, boundary delineates geographical features of institutions, and finally context focuses on

Table 2
Different aspects of institutions' characteristics.

Perspective	Description
Type	Regulative, normative, and cultural-cognitive
Sector	Finance, education/research, and manufacturing/business domains
Boundary	Regional, national, and international
Context	Internal and external

the level of institutions' dependency on a specific technology. Policy makers should recognize institutions from these dimensions in order to have a complete understanding of their characteristics.

Technology is another main component in the structure of the transition process. Technologies refer to all infrastructures and subsystems needed for development. Technology identification is a way to define knowledge borders related to a technology. There are some models to identify technology's various parts and to clarify its borders such as the measurement of technological distance [29,30], value chain of technologies [31], process-based approach [32], quality function deployment-QFD [33], and technology mapping [34]. Each of these methods has some features that make them suitable for identifying a related group of technologies in sustainable transition. Arasti and Bagheri Moghaddam [3] have presented a guideline for selecting the best method in each type of technology group.

Finally, networks are the fourth components in a system's structure when transition to renewable energy is the issue at hand. The relations among a group of actors, institutions, and technologies may be stronger than ones among other structural components. Such tight relations that create a dense configuration in the system are known as networks. Networks can be formed either in a formal (to satisfy strategic targets) or informal way. Based on the level of complexity and purposefulness of a networks' structure, they are categorized into four groups, namely supply chain networks, primordial networks, strategic networks, and invisible college networks [35]. To identify networks, they should be investigated from the following dimensions [18]: founder/year of foundation, technical focus, main actors group, network mission, network type (strategic alliance, working group association, technical committee, project networks, regional networks, and political networks), and network functions (information exchange and knowledge creation, knowledge diffusion, marketing and communicating, lobbying, and structuring).

2.2. Identification of transition dynamism

In the second step of the systemic analysis phase, a clear picture of transition dynamism should be mapped. It helps policy makers to know more about turning points, milestones, basic activities, main drivers, and important barriers that have occurred in the transition process. The process we consider for the development of renewable energies has a dynamic structure that evolves through time. The institutional approach explains the dynamism in the system that is in charge of RE development by studying actors' behaviors, while the relational approach does so by examining actors' activities stocks and flows (functions). Dynamic structures provide a system's evolution. The story of evolution is apprehensible by the help of a multi-level framework. At the micro level, actors adopt emerging systems' institutions. Established institutions are accumulated in the meso level. An interrelated set of complex institutions embedded in society finally appears at the macro level. By adoption of new micro level institutions, gradual changes occur in established institutions of meso level. Accumulation of new established institutions during a long period leads to altering of macro level complex structures and system evolution [36]. To have an understanding of this evolutionary process, its dynamism should be mapped by models such as system dynamics modeling [37,38], complexity theory [39,40], history friendly model [41], and event history analysis [42–44].

2.3. Selection of analytical approach

In the third step, a theoretical approach for analysis and policy making of renewable energy development should be selected. This selection will be done by comparing various innovation policy approaches in hierarchical levels. There are several systemic approaches for analyzing the transition process as presented by Markard et al. [8]. In this section, some of the most renowned approaches are closely examined and compared by several criteria. Based on this examination, an approach in which the features are aligned with the subject of transition process is selected. This approach will form the general framework for governance and policy making of renewable energy development in the next steps.

Considering Schumpeter's evolutionary theory as a basis, all of these approaches are divided into two groups: quasi-evolutionary and evolutionary approaches [11].

2.3.1. Quasi-evolutionary approaches

These approaches study transition as a historical pattern that is mirrored in three layers. With respect to these layers, the important structural failures are caused by social systems. They are not justifiable with only market forces [11]. Socio-technical systems are one of the approaches in this group that examine the transition of large sectors such as the transportation sector [15]. According to this approach, technological transition can be defined in three layers which are niche, socio-technical regime, and landscape [45–48]. Strategic niche management is another approach of this group that focuses on niches as a level stimulating innovation in multi-level frameworks. By having a bottom-up view, this approach tries to explain how niches are formed and how they protect innovation in the system [49–51]. In addition to these two approaches, transition management analyzes the role of niches in the success and failure of technological change. This approach perceives transition as a multi-level and multi-actor process in which niches play a major role [52].

2.3.2. Evolutionary approaches

One of the earliest approaches in this group is development blocs. Its introduction in 1950 explains that the sequence of complementarities can result in a new balanced situation by the help of some structural tensions (disequilibria) [53,54]. Moreover, there are other approaches called innovation systems that should be regarded as a dominant stream of evolutionary perspective. Innovation systems were proposed as a major research area in innovation studies at the end of the 1980s [55–57]. This approach is based on evolutionary economics and tries to explain the necessary internal and external conditions for innovation by having a systemic approach.

Innovation systems encompass all economic, social, political, organizational, and institutional factors that influence the development, diffusion and utilization of innovation [26]. Innovation systems are defined in different boundaries including national, regional, technological, and sectoral in order to obtain different analytical purposes [58,59]. Regarding its boundary, there are four types of innovation systems: national innovation systems (NIS), regional innovation systems (RIS), technological innovation systems (TIS), and sectoral innovation systems (SIS). In recent years, innovation systems are also examined from firm and international perspectives, but a concrete theory for their explanation has not been proposed up to the present time.

Innovation systems can be examined from three perspectives including structural analysis (factors-based analysis), functional analysis (output-based analysis), and system transitional analysis. In structural analysis, the main focus is on identifying the internal components of innovation systems. In functional analysis, the primary attention is on activities that are accomplished by system's components and cause the system's dynamism. Finally, transitional analysis tries to study the system's evolution and changes through time.

Table 3
Comparison of innovation systems models.

	National innovation systems	Regional innovation systems	Sectoral innovation systems	Technological innovation systems
Founder/year	Freeman [55,60], Lundvall [56], Nelson [57]	Cooke et al. [61], Saxenian [62]	Breschi and Malerba [63]	Carlsson and Stankiewicz [64]
Boundary	Geographical boundary: a country	Geographical boundary: a region (inside or among countries)	Sectors, sub sectors (including product groups and product segments)	Technology as a knowledge field, product, set of related products aimed at satisfying a particular function (competence bloc) [16]
Purpose	Comparing innovative performance of countries; analyzing the role of technological advances in economic growth; determining the socio-economic policies and strategies for stimulating innovation in a country	Determining a region's economic performance: regional innovation policy	Analysis of innovation in different sectors; development of industrial policies and strategies	Analyzing technological development from structural and functional perspective; identifying drivers and barriers of development; technological development policy making
Similar approaches	Neoclassic economic growth models; Porter's diamond model; triple helix	Industrial district [65]; Technopoles [66]; Innovative milieu [67]; Learning region [68]	Industrial economics (structure, conduct, performance); transition costs approach; sunk costs model; game theoretical model of industrial economics literature; econometrics studies [69]	Competence bloc [70,71]; Large technological systems [72]
Structural analysis	Narrow: actors and relations interacting directly with innovation			
Broad: All of social, economic, technological, and political components of a country	Four components of firms, institutions, knowledge infrastructures, and policy-oriented regional innovation	Knowledge, learning processes, actors and networks, institutions, demand	Actors, institutions, technologies, relations, and networks	
Functional analysis	Several sub functions defined in the domain of three major ones: development, diffusion, and utilization of innovation [73,74]	Classification of internal dynamics in three categories of interactive learning, knowledge production, proximity, and social embeddedness [75]	Generation of dynamics in two processes: variety creation (by R&D and innovation) and selection (by market and non-market selection process)	Seven functions of knowledge development, knowledge diffusion, entrepreneurial activities, guidance of the search, resource mobilization, market formation, and legitimacy
Transitional analysis (evolution)	The formation of institutions and firms in the country; integration of system's components	The development of networks among firms located in a region	The life cycle of industry [76,77] and long-term evolution of industries	System's evolution based on the succession model of innovation including four stages of STP motor, entrepreneurial motor, system building motor, market motor [78]
Main property	Emphasis on innovation and technological advances as a factor affecting the economic growth of countries	Emphasis on regional clusters as important factors in the innovation process	The dependency of innovation affecting factors on sector	Emphasis on economic competence: the ability to develop and exploit new business opportunities, emphasis on system dynamics and system evolution

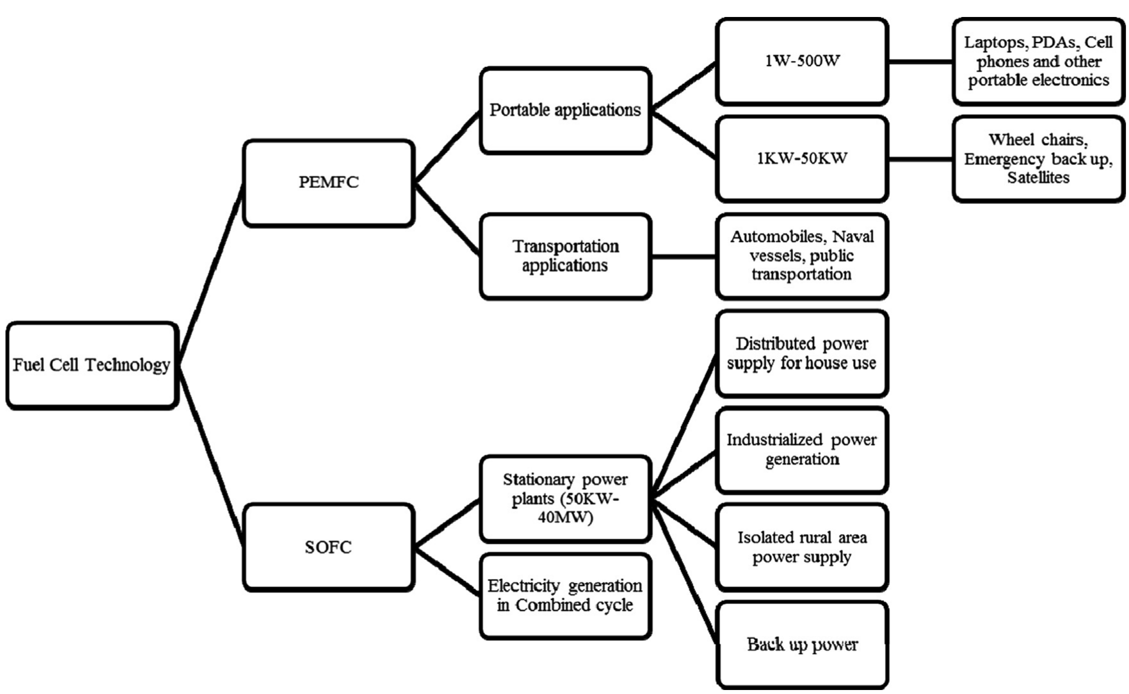

Fig. 2. FC descriptive delineation.

The comparison of various innovation system approaches based on these aspects is presented in Table 3. The selection of an appropriate approach depends on several factors. First of all, it relies on the case that is the subject of the study. When the concern of policy makers is only the development of a technology (the unit of analysis is knowledge field), TIS would be an option, and when they seek development of an industry (the unit of analysis is product), SIS is the approach they should select. Second, the aim of the study is another determinant factor in the selection of an appropriate approach. The aim of a study may be to find national development strategies, to design regulatory policies, or to describe the interactions happening in three levels of micro, meso, and macro. In each case, one approach should be selected, in which its features satisfy the aim of the research.

3. Empirical results

In this section, methodological steps of the systemic analysis phase are applied in the case of Iran fuel cell technology. Applying the presented steps in fuel cell technology development provides a strong basis for Iranian policy makers[2] to understand the current status of the transition process and to make proactively and purposefully political decisions. Here are the results of our case, fuel cell technology in Iran, presented for each methodological step.

3.1. Descriptive delineation of Iran's fuel cell transition process

The delineation process, first of all, begins with descriptive delineation or defining the unit of analysis. In the case of fuel cell technology, Iran is placed at the beginning of the technical maturity life cycle (Laboratory-scale production). As a result, fuel cell has not been introduced in the market as a commercial product. Due to lack of a mature market and commercial product, technology as a knowledge field is the appropriate unit of analysis in fuel cell technology development in Iran. Based on this decision, the primary aim of development is empowering the knowledge basis of fuel cell technology, no matter in which product or application it will be used. Along with this aim, policy makers should concentrate on constructively facilitating measures in knowledge creating parts of the socio-technical system. As Iran's FC National Strategic Plan shows, the polymer exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are two strategic technologies that should be studied in Iran. It limits the transition process to two more attractive technologies of fuel cell, PEMFC and SOFC, their applications and related products. This selection narrows down the areas that policy measures should target and saves resources from being wasted in various unrelated fields.

In the following figure (Fig. 2), the map for descriptive delineation of selected fuel cell technologies in Iran has been presented [3].

3.2. Conceptual delineation of Iran's fuel cell transition process

Conceptual delineation concerns identification of all components engaged in the development process of Iran's fuel cell technologies that were selected in the descriptive delineation. The first component is actors. To identify actors involved in a sustainable transition, there are several methods such as input–output tables and statistics on unions and industries membership, registered patents to identify related firms, and the snowball method to find actors related to a field [79,80]. In our case, a combination of these methods is deployed. First of all, by using the database of Iran's fuel cell steering committee, referring to Iran FC National Strategic Plan, and interviewing experts with the snowball method, all actors in the fuel cell technology development are identified. Then, all actors are grouped into four categories namely universities, governmental research institutes, private firms, and governmental organizations (including facilitators and regulators). In order to understand the contribution of actors in the transition process, the value chain of fuel cell technology is mapped, and the role of each actor's group in the chain is determined (Table 4). According to Nygaard [81], the value chain of fuel cell technologies consists of the following three chains:

- Upstream service providers: Material suppliers (catalysts, electrodes, membranes, polymers, ceramics), component suppliers (pump, stack components, reformer), manufacturers (design, simulation and manufacturing fuel cell systems).
- Downstream service providers: Energy supplier (contracting, power plants, utility companies), end users.
- Intermediary organizations: R&D support, financial services, policy making orgs., information exchange.

Identification of actors in fuel cell technology development has several advantages. First, it depicts all stakeholders whom our policies will affect or are influenced by. Knowing these relations, policy makers can modify the behavior of relevant actors by regulatory policy measures. Second, policy makers can draw some conclusions by examining actors categorized in the proposed framework. For example, as it appears in Table 4, a large part of actors are concentrated on R&D activities. They perform activities to satisfy the primary function of the transition process, knowledge development. However, a large part of these actors are universities and governmental research institutes. The lack of the private sector's participation in R&D activities is clearly apparent through this analysis. Being a developing country with an unstable political–economic condition on the one side, and having the large deposits and usage of oil and gas on the other, poses a heavy investment risk on pure R&D activities in alternative clean energies. This is a powerfully preventive force for the involvement of private firms and R&D institutes. In the best conditions, they prefer to invest on more reliable approaches such as assembling fuel cell technologies' parts imported from other countries or providing energy services to customers. The private sector should be engaged in R&D activities in order to prevent governmental monopoly in the future and make technologies closer to the market. This can happen by bringing facilitating measures aiming to decrease the investment risk and to add attractiveness in fuel cell studies partnership.

The second component of a system's structure is institution. In Iran's fuel cell technology case, the only formal institution that has been passed by governmental agencies is the Iran FC Strategy Plan. It is a formal-regulative institution which covers all aspects of a development program including finance, education/research, and manufacturing/business domains. It has been designed in a national boundary and the level of its dependency to a specific technology is internal. This institution is aligned with General Policies of the Fourth Economic, Social and Cultural Development Program (designed and passed by Iran's presidency) and encompasses organized solutions for technology development. The Iran FC Strategy Plan, as the only regulative and official institution, has led to some positive actions: first and foremost, it has provided enforcement over actors (R&D institutes and Private firms) to work on a unified framework. Second, according to this institution, all efforts devoted to developing fuel cell technology should be

[2] The central Iranian policy maker in fuel cell technology is Iran's Fuel Cell Steering Committee.

Table 4
Actors in Iran's fuel cell technological innovation system.

Group	Actors	Upstr. Ser. Pro.			Downstr. Ser. Pro.		Intermediary Org.			
		Material supp.	Comp. supp.	Manuf.	Energy supp.	End users	Policy making	R&D support	Financial ser.	Info. exchange
University	Isfahan Univ., Tehran Univ., Shiraz Univ., K.N. Toosi Univ., Tabriz Univ., Ferdowsi U of Mashhad, Tarbiat Modarres Univ., Iran U of Sci. and Tech., Sharif U of Tech, Razi U of Kermanshah							*		
Gov. research inst.	Renewable Energy Org. of Iran, Iran Khodro Co., Chemical Industrial Res. Ins., Ins. for Adv. Materials and new energies, Iran Polymer and Petrochemical Res. Ins., Energy and Material Res. Ins., Petroleum Industry Res. Ins., Niro Res. Ins. (RE Dep.), Scientific and Industrial Res. Org. of Iran, Joint Res. Centre of Rafsanjan Industrial Complex and Univ. of Vali-Asr, Fuel Cell Tech. Res. Center, Isfahan Eng. Res. Center							*		
Gov. Org.	Iran Fuel Cell Steering Committee, Iran's electricity supply Co (Tavanir), Iran Ins. of Standards and Industrial Res., Registration of Trademarks and Intellectual Property Org., Petroleum Ministry, Ministry of Industry and Trade, Ministry of Sci., Res. and Tech., Renewable Energy Org. of Iran, Environmental Protection Org., Iran Tech. Cooperation Office						*		*	*
Private firm	Taghtiran Kashan Co., Rail Sanat Dena Co., Parsian Poya Polymer Co., Advanced Material Development Co., Iran Nasb Niro Co., Magfa, Ghods Niro, Niro Battery, Mapna, Pilar Energy Co., Perisa Energy, Mokarar Co., Hydrogen Age Tech. Co.			*	*					

Table 5
Fuel cell technology's main parts.

Fuel cell sub technologies	Parts	
Stack components	Electrolyte support Electrolyte Flow field plate Inter-connector	Gas diffusion layer Gasket Electrode Membrane electrode assembly
Sub systems	Controller system Air management system	Water management system Heat management system
Fuel processing technologies	Storage technologies Distribution technologies	Production technologies
Simulation and design technologies	Fluent (Stack) Ricardo (FC systems) FC power software	Star CD (Stack) Lab view MATLAB/Simulink
Interface for application	Transportation application Portable application	Stationary application

connected to two strategic choices: PEMFC and SOFC. It has narrowed down available options and has stopped waste of resources in other alternatives. Third, it imposes taxes and pricing policy measures on actors in order to oblige them to behave according to its rules and regulations. Finally, it has appointed some public organizations, such as the Renewable Energy Organization of Iran, to support research projects in strategic fuel cell technologies. This decreases part of the investment risk of doing business in an emerging field of study.

The next component in conceptual analysis is technology. In our study, technology mapping is chosen for recognizing technology's components in two selected types of PEMFC and SOFC (identified units of analysis). Table 5 presents this systemic arrangement [3].

The technology breakdown in technology mapping shows five major sub technologies which compose a fuel cell technology. This classification is helpful for policy makers: First, it gives a general knowledge about technical aspects of technology they study by explaining technology components and sub components. Second, one of the major tasks in the policy making process is determining R&D priorities in the development of a technology. This process has been called portfolio strategy development [82]. In determining R&D priorities, the first step is technology identification. Mapping technology components in a systemic analysis phase assists policy makers to achieve the first required step in defining R&D priorities and technology identification.

Finally, a network is the last component in a system's structure of fuel cell development. In the case of Iran, there are some informal scientific networks whose borders are extremely uncertain and temporary, so they are disregarded from our current examination. There are also several science and technology collaborative networks of which their area of concentration is not limited to fuel cell technology, and encompasses larger areas of knowledge [83,84]. Nevertheless, the Iran fuel cell steering committee, a group of decision makers from seven ministries, is the only formal network existing in FC development. Table 6 presents a short description of this network.

Table 6
Identification of networks in Iran fuel cell development program.

	Iran fuel cell steering committee
Founder/year	Fuel cell development council/2007
Technical focus	Policy making; regulation
Main actors	Ministries of power, petroleum, science research & technology, and industry & trade; Iran technology cooperation office; Renewable energy org. of Iran; Environment protection org.
Mission	Supervising and monitoring accurate performance of all items in Iran FC strategy plan
Type	Political networks
Function	Structuring

The formation of regulatory networks prior to the formal scientific and legitimizing ones indicates several weaknesses in Iran's fuel cell development program that should be addressed in the policy making phase. In the first one, it shows that the development of fuel cell technology is highly under control by the governmental plan. As it is discussed in development economics, frequent governmental intervention in technology development is condemned because it kills entrepreneurship which is the heart of innovation. The second weakness refers to lack of networking and knowledge sharing in the R&D community including universities, governmental and private research institutes. There are several R&D institutes according to actor analysis in Iran's fuel cell TIS with almost no scientific network among them. It restricts the boosting of acquired knowledge and prevents the creation of synergy among heterogeneous actors. One of the major causes of this weakness is lack of patenting rules that preserves the right of innovators in knowledge sharing. The second cause may be laid in minimal investment and financial support from collaborative knowledge networking activities such as conferences, seminars, and scientific associations. The final weakness point is the absence of legitimizing networks such as public associations which defy the use of a new technology against traditional competitors. They facilitate the transition process and hasten the progress of technology development by providing support from advocacy coalitions. The nonexistence of such networks has led to slow and difficult progress in program development.

3.3. Identification of Iran's fuel cell transition's dynamism

Based on the event history analysis, the evolutionary process of the fuel cell transition process in Iran is as follows.

Iran's fuel cell evolution can be arranged in three stages. In the first stage, there were diverse and disparate researches and executing activities regarding FC technology. The main purpose of such activities was the justification of actors to get engaged in the emerging technology. Consequently, research and scientific success was always used to legitimize fuel cell development among industry and government decision makers. In this period, due to the lack of a concrete plan to financially support initiatives, a large part of the activities were handled by voluntary activities in universities. In the second stage, the major focus was on organizing related activities by passing a national document named Iran fuel cell strategy plan. In addition to its guiding role, this plan brought collaboration of various actors in defining fuel cell research priorities, identifying knowledge and human resource potentials, and developing technology strategies. Finally, in the third stage and by passing the FC strategy plan, all activities were concentrated on two options of PEMFC and SOFC. This selection helped to focus all efforts on narrow options and to manage financial resources properly. In general, although there were many obstacles in handling measures developed in the plan, the fuel cell technology council stressed on pursuing them almost successfully up to now. In this respect, Iran's success in producing the 5 kW fuel cell CHP system which provides motivation among actors is one of several outputs in FC research activities.

The evolution of Iran fuel cell technology shows events that have occurred in the past and have yielded the level of performance that Iran experiences now. Based on this performance, policy makers can find shortcomings in the system of fuel cell technology development. Inferred from described dynamisms, one of the main shortcomings is separation of industry from universities. During the first and second stages of development, universities devoted considerable effort to expand the knowledge of fuel cell technology. However, industrial firms were not engaged in their activities because of the high risk embedded in emerging technology research. The effect of this separation was twofold: lack of available funds for universities' research due to insignificant interest of industry and missing the link between technology and market because of poor collaboration among production firms in industry. Another important shortcoming in fuel cell technology development is the ignorance of strategic plan revision. Both environmental factors and internal capabilities change throughout time. Changes in these factors drastically impress the strategies and decisions that policy makers have made. In Iran, although the government developed the Iran fuel cell strategy plan in 2006, it needs to be revised. This revision should encompass all changes that have happened in Iran's capabilities, technological progress, and market structures. It should also consider the new trend of fuel cell technologies development. By reviewing these changes, Iran's previous strategies such as the selection of two strategic technologies, PEMFC and SOFC, may be revised in the current situation.

3.4. Selection of analytical approach for policy making

Selection of an appropriate analytical approach is based on the degree of alignment between the approach's features and case specifications. All of the systemic models presented in the last methodological step can be compared from various perspectives [11,13–16,85]. Based on these researches, having the capability of analysis in levels of technological, national, regional, and sectoral, considering the dynamism of the system, and emphasizing the role of actors, institutions, networks, and innovation systems can be selected as the systemic model of innovation in the case of fuel cell technology development. Furthermore, as technology is the unit of analysis in the case of Iran's fuel cell development, the technological innovation system is the most practical type of systemic model that policymakers can opt for. Nevertheless, Lundvall et al. say that in developing countries such as Iran, the national system of innovation has not been formed completely, and it is preferred to implement TIS in combination with NIS as policy making tools [86].

TIS provides all analytical frameworks that are required for the policy making phase. According to TIS literature, necessary events for transition should be performed through seven functions [87]. Analyzing the system from a functional perspective provides a complete picture of the system's performance. Relating the system performance to structural components leads to identifying the role that each component (actors, networks, and institutions) has in performing the purpose of the system, generation, diffusion, and deployment of innovation. Finally, by finding the causal relations among different system functions, the dynamics of evolution can be mapped. Causal loops in each period of evolution are keys to design pertinent policy measures [78]. These policy measures stimulate the development process and remove obstacles in each period.

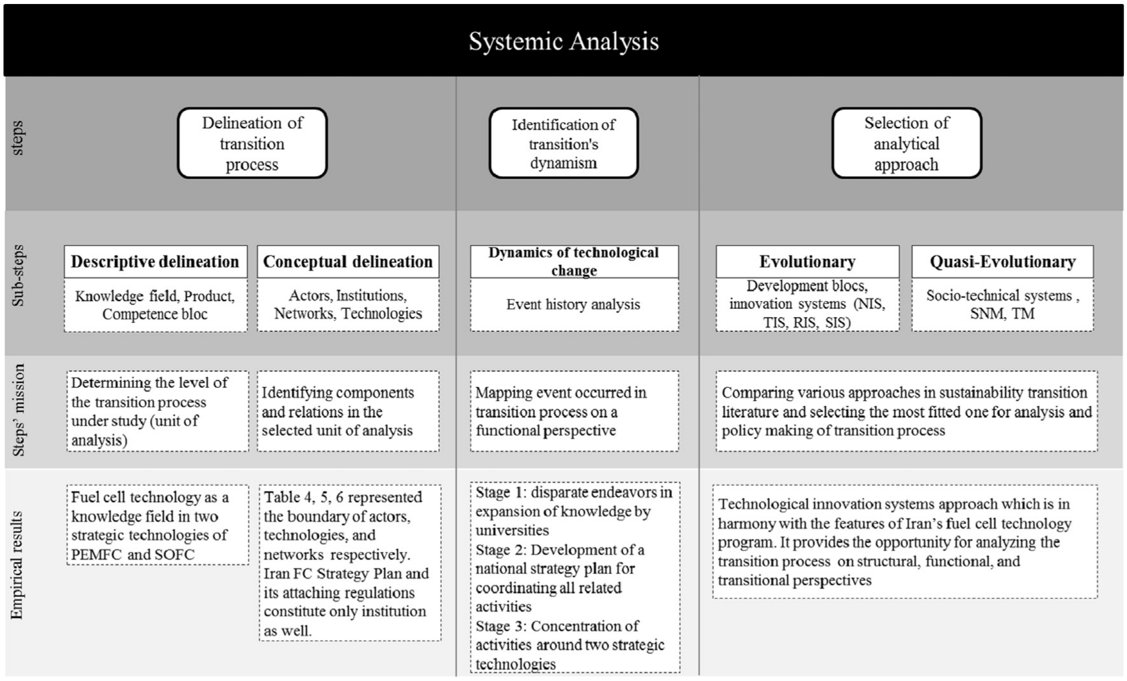

Fig. 3. Graphical representation of methodological steps and empirical results.

4. Results and discussions

In this paper, the governance of sustainability transition was investigated in renewable energy technologies. Although a lot of research has been done in this area, this study has attempted at presenting a clear and coherent framework for the primary phase of its governance at the national level, the systemic analysis phase. Fig. 3 depicts the summary of developed methodological steps of this phase and results attained from Iran's fuel cell technology program.

In this respect, the main characteristics and contributions of this paper that separate it from similar researches are as follows:

1. It has seen the subject of governance in the development of renewable energies from a process-oriented view. Based on this viewpoint, it is divided into two phases of systemic analysis and policy making. The process-oriented view helps analysts provide a step by step approach for gathering requisite inputs for further political decisions. These steps are integrated (being in harmony with one another and toward a same goal), holistic (covering different conceptual aspects of innovation systems literature), practical (presenting operational frameworks for real case application), and process-oriented (providing sequential input–output steps).
2. It has made a distinction between two different definitions in its system delineation step. One regular form of setting a boundary is the identification of system's components or conceptual delineation. However, the framework has accommodated the other definition from system delineation which is the unit of analysis or descriptive delineation. Descriptive delineation establishes the level that analysis should be done and conceptual delineation identifies all components and relations in the chosen level of analysis.
3. Having a methodological step about the selection of an appropriate analytical approach in governance of transition is another characteristic of this study. This selection can be done by matching the approaches' features with the cases' specifications. In this respect, the paper has reviewed a diverse range of approaches in the domain of sustainability transition. The output of this review has been a thorough comparison among different transition approaches and the expression of their basic features.
4. The final characteristic is concerned with presenting a practical framework for performing each methodological step in real cases. This paper has applied the methodological steps in the case of fuel cell technology development in Iran. In addition to validating the proposed steps, the case study contains valuable insights (such as existing drivers and shortcomings of transition, general structural components engaged in fuel cell development, a short narrative story of development process) from the development of fuel cell technology in Iran. This may be the interest of policy makers and practitioners especially in developing and oil-dependent countries.

5. Conclusion

Development of renewable energies is facilitated in oil-dependent countries just by governing its complicated transition process to eliminate their strong inertia. In this respect, systematic analysis of the current status in a transition process is considered the first requisite phase. The paper has divided this phase into three consecutive steps including delineation of transition process, identification of transition dynamism, and selection of analytical approach. The results gathered from performing these methodological steps provide a concrete basis for political decisions in further phases. Applying proposed steps in the case of Iran fuel cell technology development proved their applicability in real case problems. Furthermore, it brought general knowledge regarding Iran's fuel cell development program for practitioners and policy makers.

While this study has attempted to cover the subject of sustainability transition thoroughly, it has some weaknesses which can be

improved in further researches. Up to now, three steps are introduced for the first phase in the governance of RE transition. However, there is another step called performance analysis, which can be considered in the systemic analysis phase. Performance analysis aims to identify all drivers and barriers in the transition process. The policy making phase will be promoted by having these inducing and blocking mechanisms of transition. Designed policies should strengthen each driver and weaken each barrier to facilitate development. In innovation systems literature, there are four ways to assess the performance of a system: output-based performance [88,89], function-based performance [90,91], structure-based performance [19,20,24,92], and causal loops-based performance [78,93]. All of these methods view performance analysis from only one perspective (except [93] which combines function-based and causal loops). Hence, designing a methodology for analyzing the performance of the transition process from three perspectives, namely macro (causal loops among functions), meso (functions), and micro (structure) can be a future research to complete the systemic analysis phase. In addition, having a framework for selecting policy alternatives to address each of the drivers and barriers identified by performance evaluation is another future area of research.

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